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Final

RESEARCH NEEDS: PRIME-POWER FOR HIGH ENERGY SPACE SYSTEMS

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By the year 2000, an increasingly large portion of our national defense will depend on space-based systems. As part of a broader set of new research initiatives in support of space systems, the Air Force Office of Scientific Research is sponsoring basic research that may be applicable to the development of megawatt-level space prime-power systems. (The emphasis of this particular new initiative is prime-power versus pulsed power including power conditioning, such as fly-wheel or inductive storage, for which there are existing programs.) OVER

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19. KEY WORDS (Continued)

20. ABSTRACT (Continued)

To assist AFOSR, R & D Associates organized a special conference on prime-power for high-energy space systems, compiled the proceedings of the conference, and provided a review document identifying basic research areas in support of future space prime-power development. This document is the Appendix of the present report. The intent has been to focus on basic vs applied research and to provide guidance and assistance to prospective researchers. In this last regard, a bibliography of space prime-power is contained in the appended document.

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I. INTRODUCTION

By the year 2000, an increasingly large portion of our national defense will depend on space-based systems. Extrapolation of present trends indicates that prime-power sources operating at megawatt levels and beyond will be needed. These power levels must be achieved at significantly higher values of specific power (w/kg) and energy (w-hr/kg) than are presently available in order to satisfy defense needs for maneuverability and survivability. While steady progress has been made and new concepts have provided the potential for further improvements, substantial gains over the next two decades will probably require investment in basic research examining fundamental processes and phenomena in power conversion, material behavior, surface interactions, etc. As part of a broader set of new research initiatives in support of space systems, the Air Force Office of Scientific Research is sponsoring basic research that may be applicable to the development of megawatt-level space prime-power systems. (The emphasis of this particular new initiative is <u>prime</u>-power versus <u>pulsed</u> power including power conditioning, such as flywheel or inductive storage, for which there are existing programs.)

To assist AFOSR, R & D Associates organized a special conference on prime-power for high-energy space systems, compiled the proceedings of the conference, and provided a review document identifying basic research areas in support of future space prime-power development. This document is the Appendix of the present report. The intent has been to focus on basic <u>vs</u> applied research and to provide guidance and assistance to prospective researchers. In this last regard, a bibliography of space prime-power is contained in the appended document.

II. REVIEW OF SPACE PRIME-POWER CONFERENCE

As part of an assessment of research needs in the space prime-power area, a special conference was convened at the Omni International Hotel in Norfolk, VA, 22-25 February 1982. The intent of the Conference was to review the state-of-the-art of space prime-power technology, including new or advanced concepts, and to discuss research needed for progress toward megawatt power levels. The Conference was attended by over 190 scientists and engineers from universities, government, and private organizations. Over eighty papers were presented, including discussions of chemical, nuclear and radiant energy techniques, power conversion, heat rejection, materials, chemical and fluid physics, and also reviews of power requirements for future NASA and DoD systems. The Conference agenda is displayed in Fig. 1, in terms of technical topics, session chairmen, and first authors. Table I provides the Table of Contents of the Conference, listing the authors and titles. Fig. 2 displays the names and affiliations of the Executive Committee members, whose interest and efforts allowed a successful meeting to be organized and convened in a matter of three short months.

From the session on prime-power needs, distinctions could be drawn between the continuous power levels required by NASA and DoD missions involving long-term propulsion and station-operation, and the intermittant needs of some proposed DoD missions for very high power levels (10^7-10^8 w) for several seconds or longer. The latter DoD requirement, which does not have routine parallel requirements in NASA, tends to broaden consideration of prime-power technology options. For example, it may be reasonable to expect that continuous multimegawatt power for orbit changes (including deep space missions away from the sun) will require space-nuclear

reactor systems. A few second burst of 100 megawatts, however, might be better provided by a chemically-driven MHD system. In support of possibly broader requirements for high power, it may be anticipated that AFOSR would have broader research interests in the space prime-power area.

The first two days of the Conference were largely devoted to a review of technology so that basic research scientists could learn from technologists about the existence of various systems and critical problem areas. Chemical sources were reviewed, including batteries, fuel cells, and combustion-driven MHD. Related power conversion techniques were also discussed in the form of turbogenerator developments and several MHD methods connected to chemical sources. (Other MHD systems, not strictly chemically-driven, were also described on the first day.)

Discussions of nuclear sources included both developments from earlier NASA/AEC efforts, such as the present SP-100 program, and also advanced concepts in the form of rotating-fluidized bed systems. Attention was also given to safety issues for space nuclear power, shielding considerations, and research needs. The nuclear session was followed by a short session on power conversion technologies (Brayton, Rankine, thermoelectric), which are often closely connected to nuclear sources. The needs for improved data on high temperature materials and better theoretical understanding, (e.g., thermoelectric properties and scaling) were also discussed.

The session on radiant systems covered a range of technologies and concepts involving photons in one way or another. These technologies included photovoltaic concepts (tandem photocells and thermal-photovoltaic), solar-thermal approaches, and various possible ways of generating laser light for transmission of power through space (solar-, nuclear-, optically-

pumped lasers). New concepts for converting light to electricity were also described, such as radiation-driven MHD, plasma-diode conversion of laser light, and a device to convert light to RF (actually demonstrated at the Conference).

The last full day of the Conference tended to concentrate on scientific research issues, but also included descriptions of technology and concepts. It was readily anticipated prior to the Conference that materials research would be a critical requirement for progress toward high power in space. Indeed the session on materials was quite extensive, comprising 15 papers on subjects such as surface modification techniques, reactor materials, ceramics, materials testing, structural characterization, and electrical insulation. Closely related to materials research were topics in chemical physics research and thin films, discussions of which completed the morning's activities.

In the afternoon, thermal energy was considered in various manifestations: thermionic energy conversion research and technology, heat rejection techniques, and thermal-stress analysis of large space-structures. The session on thermionics included a review of the DoE program in thermionic research, in addition to descriptions of systems such as in-pile thermionic diodes and prospects for performance improvements by understanding and controlling particle collection geometries. Advanced radiator designs, such as liquid droplet and liquid metal film concepts, were discussed in the session on heat and systems. This session also included consideration of heat pipes, thermal management of power systems, and software for analysis and optimization of power systems. Problems and uncertainties of analysis and prediction of large space-structures, such as required for support of solar arrays, mirrors, radiators, etc., were also discussed.

The last day of the Conference consisted primarily of a morning session in which the session chairmen summarized discussions that took place both within their formal sessions and also at the discussion symposia that concluded each (very full) day of the meeting. (In order to complete the eighty papers of the Conference in a single-session format, questions during the formal sessions were limited to ones of clarification. Detailed questions and answers were obtained in writing and posted at the discussion symposia for inspection by Conference attendees and for continued discussion by interested parties.) On the last day, the session chairmen were also offered the opportunity to present their personal viewpoints on space prime power.

The Special Conference on Prime-Power for High-Energy Space Systems provided a useful opportunity for research scientists and technologists to educate each other on problems and progress in space prime-power. Although the AFOSR interest is basic research, the Conference also served as a forum for description of systems, concepts, and programs with particular mission requirements, and for discussion of research in support of specific devices or needs. The proceedings of the Conference, (consisting of over 1700 pages of text and view graph copies), were compiled and distributed to Conference attendees.

Mon. 22 Feb.

0800 Registration

0900 **I. Needs**
(Turchi; Hyder)
1. Hartke
2. Mullin
3. Cohen
4. Woodcock; Silverman
5. Caveny

1100 **II. Chemical Sources**
(Barthelemy)
1. Clark
2. Brown
3. Stedman
4. Oberly

1230 **LUNCH**

1330 **III. Chemical/MHD**
(Barthelemy)
1. Dicks
2. Smith
3. Louis
4. Bangerter
5. Massie
6. Jackson
7. Pierson
8. Goswami
9. Swallom
10. Seikel
11. Koester

1630 **Discussion Symposium**
(Vondra)

Tues. 23 Feb.

0800 **IV. Nuclear Sources**
(Angelo; Lee)
1. Buden
2. Fraas
3. Fitzpatrick
4. Thompson
5. Elsner
6. Powell; Myrabo
7. Lee
8. El-Genk
9. Jones
10. Ranken
11. Bartine

1100 **V. Power Conversion**
(Layton)
1. Thompson
2. Peterson
3. Bland
4. Stapfer

1200 **LUNCH**

1300 **VI. Radiant Systems**
(Severns)
1. English, Brandhorst
2. Loferski
3. Loferski
4. Holt
5. Conway
6. Phillips
7. Miley
8. Walbridge
9. Britt
10. Finke
11. Freeman
12. Lee, Ja
13. Freeman

1700 **Discussion Symposium**
(Guenther)

Figure 1.

Wed. 24 Feb.

0800 **VII. Materials** (English)

1. Saunders
2. Morris
3. Ling Yang
4. Rossing
5. Nahemow
6. Cooper
7. Levy
8. Sarjeant
9. Sundberg
10. Milder
11. Milder
12. Banks
13. Rice
14. Blankenship
15. Gilardi

1045 **VIII. Chemical Physics** (Junker)

1. Rabitz
2. Rosenblatt
3. Donovan

1145 **LUNCH**

1245 **IX. Thermionics** (Junker)

1. Ling Yang
2. Huffman
3. Lawless
4. Merrill

1345 **X. Heat/Systems** (Badcock)

1. Haslett
2. Taussig
3. Bruckner
4. Ernst
5. Ernst
6. Fowle
7. Teagan
8. Berry
9. Thornton

1700 **Discussion Symposium** (Hyder)

Thurs. 25 Feb.

0900 **XI. Summary** (Turchi)

1. Barthelemy
2. Vondra
3. Angelo
4. Layton
5. Severns
6. Guenther
7. English
8. Junker
9. Badcock
10. Hyder

"The AFOSR FY'83 Space Initiatives"
Bryan

1200 Conference End

Executive Committee Working Session

Figure 1. (Continued)

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TABLE 1. CONTINUED

AFOSR SPECIAL CONFERENCE ON
PRIME-POWER FOR HIGH-ENERGY SPACE SYSTEMS

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Figure 2.

III. COMMENTS ON SPACE PRIME-POWER RESEARCH

The development of prime-power for high-energy space systems is an extremely broad-based and quite intricate endeavor. Fortunately, the nation has technologists, scientists, engineers, administrators, also military officers that have dedicated many years of their lives to such effort. Substantial programs have existed at least for two decades within the Air Force, NASA, and the DoE (and its antecedents). Many hundreds of millions of dollars have been spent during this time. Considerable progress has been made (and, in some cases, set aside). Major programs of applied-research and exploratory-development exist at AFWAL and at NASA laboratories. The results of these programs have been superlative. In order for AFOSR to enter with a new initiative on space prime-power and have a significant impact (at the level of $\sim$ 1-2 M$/yr), research must be sponsored that is special, uniquely the province of AFOSR, and *not merely a weak echo* of more substantial programs. Such a unique approach would be sponsorship of research that is longer range, more fundamental (or abstract), and more broadly applicable than the particular efforts other organizations must conduct in order to ensure steady nearterm progress.

In the review document, included as an appendix to this report, a survey of space prime-power research and technology indicates that three common areas exist that together would satisfy the need for broad applicability: 1) characterization and design of materials; 2) fluid interactions; and 3) plasma interactions. In each of these areas, it is important to emphasize the general, fundamental, or ideal solution. It would be too easy, otherwise, to become a supplement to particular applied research tasks and thereby lose the unique role AFOSR could play in space prime-power. For example,

it is not unlikely that present techniques on material modification by ion bombardment could be extended. In what directions should they go? How will we know when we get there? What limits are there fundamentally? The idea of designing bulk materials, large surfaces, etc. to obtain a desired function may soon become as commonplace as video-game chips. There are many possible applications. The AFOSR initiative could insure that space prime-power is one of them.

Another special role that AFOSR could play is in providing the basis for training the researchers and technologists that the nation will need to pursue space prime-power research over the next two or three decades. It is altogether possible that a lapse in support for an area of technology, together with lucrative competition from other technical areas, will result in a severe shortage of experienced personnel just when requirements are established for high levels of space prime-power. It is already almost the case that the national capability in thermionics will be severely diminished by DoE cuts. The so-called "lost decade" of space nuclear power could be continued. Such fluctuations are made worse by the timescales required for developmental efforts, in particular life-testing.

IV. CONCLUDING REMARKS

The activity recently completed by R & D Associates in support of AFOSR was necessarily quick and broad. It was important to gather the space prime-power community together on rather short notice, and the resultant conference, while acclaimed a success, did not provide for organizational feedback. It may be useful for AFOSR to organize or participate in future conferences on space prime-power research. Such meetings could serve to gather the AFOSR program periodically into closer contact with technology efforts, and might be held with the cooperation and guidance of an executive committee that advises the AFOSR program.

A distinct omission in evaluation of space prime-power research for the AFOSR initiative has been the lack of consideration of Soviet efforts. This deficiency could probably be corrected with support to AFOSR from AF-FTD. Since, undoubtedly, AFWAL tracks Soviet progress in prime-power, much of the information and guidance could be supplied by AFWAL. For the time and resources available, the present study has provided: a well-attended conference, proceedings ($\sim$ 1700 pages) distributed to the prime-power community, and a review document and bibliography to assist prospective researchers.

Special thanks are due to members of the Executive Committee who took the time and effort to assist AFOSR in convening its conference.

APPENDIX A. DRAFT DOCUMENT FOR AFOSR RESEARCH NEEDS: PRIME-POWER FOR HIGH ENERGY SPACE SYSTEMS

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I. INTRODUCTION

Recent study* of potential requirements for prime-power by Air Force space systems indicates that steady electric power levels approaching one megawatt will be needed by the end of this century (Figure A1). Pulsed electrical power levels in excess of 100 MW will probably also be required by various space-based future weapon systems. (Such pulsed levels may be repeated and sustained long enough to require significant heat and mass transfer, resembling steady power system operation). Beyond these general statements (from historical trends and research predictions), Air Force mission needs for high power levels in space cannot be precisely specified at this time. Indeed, until megawatt space-power sources are in hand, it is unlikely that missions will be authorized that require such sources.

To reconcile the present lack of specific needs with the certain future requirement for high levels of prime-power capability, a broad-based and fundamental research program is necessary that will support efforts in the next two decades. In such a research program, the particular problems of a specific device presently under development are less important than the creation of tools, data, techniques, etc. Specific problems of the present should, therefore, be generalized to identify and solve fundamental questions. The understanding obtained will then provide the basis for developing prime-power systems that will enable the performance of future high power missions.

---

* M. E. Cohen and M. Weinter, "Space Power Technology for the Military Space Systems Technology Model". The Aerospace Corp., El Segundo, CA 90245. Aerospace Report No. TOR-0082 (2909-63)-1.

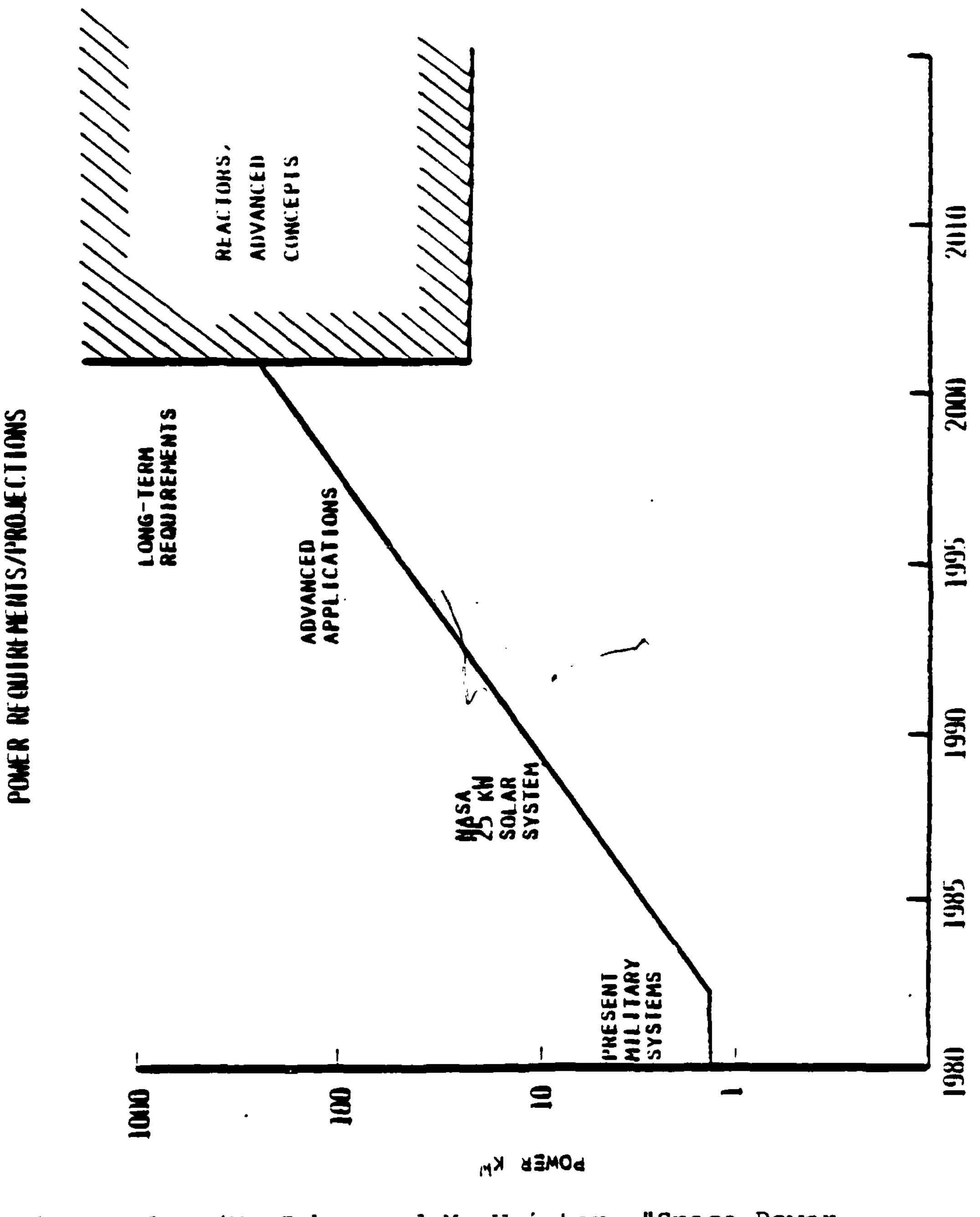

Figure A1. (M. Cohen and M. Weinter, "Space Power Technology for the Military Space Systems Technology Model").

In addition to potential requirements for high power levels, Air Force missions will almost certainly emphasize features such as low weight, small size, and survivability. Considerations of the total spacecraft and mission are unavoidable in specification of the technical approach, components, and trade-offs in the prime-power system. Such considerations may involve particular emphasis on the specific power (kw/kg) of a generator, as opposed to the specific area (m^2/kw) of the heat-rejection radiators. Thus, critical values for component performance (e.g., specific power, specific energy, efficiency, etc.) cannot be stated without reference to system design and mission requirements. Design studies have been performed that indicate the relative importance of the various elements of particular prime-power systems. Such studies will continue to be useful, but will generally depend on mission needs, especially in regard to duration, maneuverability, survivability, etc.

For example, suppose the specific power of the total system is critical to a maneuvering spacecraft mission. By estimating the power converter weight compared to radiator weight, the need for a factor of two increase in converter efficiency versus a 20% increase in heat-rejection temperature could be evaluated. Research emphasis could then be allocated accordingly between converter physics and high temperature material studies. It is not unlikely, however, that twenty years from now <u>both</u> higher efficiency and higher temperature will be critically important to Air Force missions. A reasonable area for basic research in support of space prime-power, therefore, would be the behavior of interfaces at high temperatures, since fundamental

understanding might assist the development of both thermionic converters and high-temperature heat transfer components. A similar process of identifying common scientific areas related to separate technical problems can be applied, in principle, to all factors that control the performance of prime-power systems. Such factors include loss of fatigue strength at high temperature, utilization of broad-spectrum radiant sources, particle collection in diodes, irreversibility of reactions, and many other topics that are evidenced by present limits on performance. (A list of some performance values* is presented in Table AI.)

In general, for any value of specific power, lifetime, limiting-temperature, etc., a basic reason exists for the present state-of-the-art. The reasons may be trivial ("testing was stopped at 10,000 hrs"), fundamental and fixed ("the bond energy is 0.3 eV"), or basic, but controllable in principle ("the undoped material is not matched to the raw spectrum"). It is the last category of reasons that offers research topics of greatest promise. By identifying fundamental physical limitations, understanding the controlling parameters, and then devising techniques by which these parameters can be adjusted to obtain higher performance, new levels of capability can be achieved, guiding the development of new devices, components, and systems.

A program initiative comprising the various basic research topics that will be important to space prime-power development will necessarily be quite broad. It is, therefore, likely that many researchers possessing the

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* Compiled from the proceedings of the AFOSR Special Conference on Prime-Power for High-Energy Space Systems, 22-25 Feb 1982, Norfolk, VA.

TABLE AI. SAMPLING OF PRIME-POWER TECHNOLOGY NUMBERS

(Compiled from Proceedings of Special Conference on Prime-Power for High Energy Space Systems, 22-25 February 1982, Norfolk, VA)

Item	No.	Comment
Battery specific power	800 w/lb	(AgZn, 1 min)
Fuel cell specific power	50 w/lb	(Shuttle orbiter)
Space nuclear power		
Reactor specific power	25 w/lb	(for 100 kW_e design)
RTG specific power	2.4 w/lb	(Galileo)
Solar cell efficiency	18 %	(GaAs)
Array specific power	30 w/lb	(GaAs)
Thermoelectric efficiency	8 %	(SiGe)
Thermionic diode efficiency	15 %	

expertise required to address fundamental issues will be unfamiliar with the needs and possibilities of the space prime-power area. This document attempts to provide a brief review of space prime-power systems and research needs. The present review is based largely on the AFOSR Special Conference on Prime-Power for High-Energy Space Systems, 22-25 February 1982, Norfolk, Virginia. In particular, the bibliography has been compiled from the individual bibliographies of over eighty papers presented at the Conference, and should assist prospective researchers in obtaining both broad and detailed information on specific topics. Additionally, some guidance is provided on useful distinctions between basic and applied research in support of Air Force needs.

II. BRIEF OVERVIEW OF SPACE PRIME-POWER

There exist many techniques for obtaining electrical power in space. The relative merits of particular techniques and the optimum combination of components and processes depend primarily on mission requirements. It is useful to divide prime-power systems <u>functionally</u> into three parts: 1) energy generation; 2) conversion of source energy into electricity; and 3) rejection of thermal energy generated by inefficiencies in the generator and/or converter. The first functional part may not actually be contained in the spacecraft. For example, the sun or a laser beam could supply photon energy. Also, the energy source may be replenishable, in terms of chemical reactants, for example*.

For each of the three functional parts, there are reasonably distinct <u>technical</u> categories. In the energy generation area, nuclear and chemical processes are the fundamental sources; it is useful, however, to treat radiant source technology (solar, laser, microwave) as a major category. ("Which came first, light or mass?", is beyond the scope of the present document.) In the area of energy conversion into electricity, three main categories exist: 1) <u>photoelectric</u> - photon energy converted directly to electricity, typically by direct interactions of photons and

*The distinction between energy sources and energy storage (for pulsed-power or load-levelling) is somewhat arbitrary, but can be made in terms of physical/chemical processes. That is, if the processes are the same as for a source that would be launched from the earth, then it is reasonable to treat any device, even if energized in space, as an energy source (example: batteries). If the device would not be launched in an energized state (example: high speed, rotating flywheel), then it is more useful to consider it part of the power conditioning system (or in some instances, power conversion).

electrons; 2) thermal - heat converted to electricity by direct means (Seebeck effect, thermionic diode) or indirect means, involving transformation of heat into mechanical energy and then into electricity (MHD, Brayton, Rankine, etc.,-cycles); and 3) chemical - reaction energy converted to electricity (battery, fuel-cell, beta-decay). Rejection of heat from the prime-power system also has three main categories: radiation, storage, and mass ejection. The last two categories can be utilized in missions that require short intervals of high prime-power levels; radiation is the only choice for steady-state power processing. (Storage is also used beneficially in some systems as a load-leveller). A diagram summarizing the functional and technical areas of space prime-power is given in Figure A2.

MATRIX OF SPACE PRIME-POWER TECHNOLOGY

FUNCTIONS

	Energy Generation	Conversion to Electricity	Heat Rejection
TECHNIQUES	RADIANT Solar Laser Microwave	PHOTOELECTRIC Photovoltaic Laser inverter μwave antenna	RADIANT Conventional Liquid
	NUCLEAR Isotope Reactor Fusion	THERMAL Dynamic cycle MHD Thermoelectric Thermionic	EJECTION Open-cycle
	CHEMICAL Combustion Reaction	CHEMICAL Battery Fuel-cell Nuclear emission	STORAGE Molten salts

Figure A2.

III. BASIC VS APPLIED RESEARCH IN SUPPORT OF PRIME-POWER

Before describing particular research topics, it is useful to discuss those distinctions between basic and applied research that delineate the responsibilities of the Air Force Office of Scientific Research in regard to sponsorship of research. As indicated earlier, AFOSR is interested in basic research issues applicable to space prime-power development, rather than specific mission-oriented devices, schemes, etc. Within the Department of Defense, funding for research is divided along both disciplinary lines (e.g., physics) and mission immediacy. Basic research is performed under DoD sponsorship at two levels of immediacy: a) directly in support of a single mission requirements (designated "6.2" for physics research) and b) applicable, but not necessarily applied, to more than one mission (designated "6.1" for physics). An example of 6.2 research would be understanding pulsed high temperature plasma radiation sources in regimes of interest for nuclear weapons simulation. Understanding plasma/surface chemistry at a level applicable to lasers, switching, and re-entry vehicles would be 6.1 research. While a variety of specific prime-power systems of Air Force interest may require research, the mission of AFOSR is to foster research at the fundamental (e.g., 6.1) level rather than to fund research and development of particular, single-mission-related devices. Other parts of the Air Force have responsibilities for such development, and also for research needed to accomplish development successfully. (Note that, in the other extreme, fundamental research not clearly applicable to some defense mission may not be of sufficiently immediate interest to qualify even for 6.1-type funding.)

In the next sections, research problems are grouped according to technology areas to indicate the sources of concern in space prime-power systems. (The bibliography has the same arrangement so that reference material can be readily accessed.) The scientific issues common to several technological problem areas comprise the research interest of AFOSR in support of prime-power for high energy space systems.

IV. BRIEF SURVEY OF SPACE PRIME-POWER TECHNOLOGY AND RESEARCH

1. CHEMICAL SOURCES

The use of chemical energy to create electricity is a well-established technology, typically found in a variety of batteries. In most terrestrial applications, battery systems appear relatively passive and the principal thrusts for development have been higher energy density, higher current capacity, lower cost, etc. Defense system applications place additional constraints, largely due to environment and limited access (e.g., underwater, in space). The basic ruggedness and reliability of battery systems are sufficiently attractive to maintain interest in extending battery performance into regimes for which other (more complex) techniques might otherwise be selected.

Fuel-cells have been developed relatively rapidly in support of space missions and can also be considered well-established technology. As with batteries, there is considerable impetus to extend capabilities to higher levels. Higher pressure operation appears to provide significant improvement. Also in common with batteries, the development of reversible (rechargeable) systems is particularly interesting. For missions in which very high power levels are needed intermittently for short durations, the use of fuel-cell reactants, such as hydrogen and oxygen, in combustion-driven MHD generators could provide a total system capability that would favor H_2/O_2 fuel-cells for modest, steady power requirements. Other reactants are, of course, possible and are under investigation. (Considerations of system concepts, while supplying additional reasons for fuel-cell development, are beyond AFOSR research interests).

Two directions for battery and fuel-cell development can be pursued. Since the basic technology is already well in hand, performance can be improved by testing devices and correcting failure modes. In some instances, performance limitations may be due to mechanical stresses (as in higher pressure fuel-cell operation) or system design may constrain the choice of reactants to fuels needed by other power modes (e.g., H_2/O_2). Gradual evolution to higher performance should be possible, even empirically. In parallel with such evolution, fundamental studies of the interface chemistry and other interactions between electrodes and electrolytes may assist in selection of candidate reactants, catalysts and structural materials. Many aspects of these studies could prove useful to other parts of the prime-power system, such as surface reactions in heat loops.

2. CHEMICAL/MHD SYSTEMS

The technology of magnetohydrodynamic (MHD) power systems is associated with chemical systems because combustion is often used to provide the necessary high speed, electrically conducting flow. Apart from this association, MHD power systems do not utilize chemical reactions to generate electricity. There are however, critical chemical processes involved in MHD generators.

Basically, MHD power generation requires that a high speed flow crossing a strong magnetic field possess sufficient electrical conductivity to allow significant currents to flow (magnetic Reynolds numbers $\gtrsim$ unity). Such currents interact with the local magnetic fields to produce an electromagnetic body force that acts against the high speed flow, converting kinetic energy into electrical energy. For gaseous or plasma flows, the electrical conductivity depends critically on the temperature (and,

sometimes, density) of the flow. The conductivity is, therefore, significantly affected by both the initial flow conditions (as provided, perhaps, by chemical combustion) and chemical processes (e.g., ionization/recombination) in the current-carrying flow. In the temperature regime that is typical of MHD power systems (0.1 - 1 eV), the conductivity and current density distributions can interact nonlinearly, providing significant variations from optimum performance characteristics (e.g., spokes).

The interaction of the conducting flow with solid boundaries (electrodes and insulators) can also be a critical area limiting MHD generator performance and lifetime. The basic physical processes of heat transfer, particle bombardment, and radiation interact closely with chemical processes of ionization, recombination, excitation, etc., at and near the solid boundaries. Nonuniform attachment of the discharge to electrodes, the degradation of insulators by particles and "triple-point" interactions (where the discharge, electrodes, and insulator meet) are just a few of the basic problem areas. Many of these problems are shared by advanced propulsion systems (e.g., plasma thrusters), so common research interests exist for AFOSR attention. Some research interests would include development of experimental and theoretical techniques and a data base on electrode and insulator materials in a high energy discharge environment.

There are MHD generator concepts and systems that do not involve high-current gas-discharges, namely, liquid-metal/aerosol systems. In such generators, the conducting flow consists not of a gas, seeded with metal (e.g., cesium) for ready ionization, but a liquid-metal "seeded" with gas bubbles. Expansion of these bubbles provides the working mechanism by which heat energy (in the gas and liquid) is converted into flow kinetic energy. The liquid metal allows

a high conductivity path for electrical currents between the generator electrodes. Interaction of these currents with magnetic fields again provides the electromagnetic forces that oppose the fluid flow and convert kinetic energy into electric energy.

Two areas of research in liquid metal/aerosol MHD generators are interactions of the hot liquid-metal flow with solid boundaries, and the mechanics of two-phase, multi-component thermodynamic flows. Both these areas occur in other parts of prime-power systems, such as liquid-metal thermodynamic cycles, heat pipes, and liquid-film or -droplet radiator systems. Common research questions can,therefore, be expected.

3. NUCLEAR SOURCES

Nuclear sources for electric power generation are well-established in terrestrial applications at very high power levels (>Mw) and in space-based systems at levels presently adequate for many significant missions (<10 kw). The space-based systems (in the past or present U.S. inventory) include the radioisotope sources (e.g., radiothermal generators or RTG's) and dynamic-cycle approaches. The high-power systems are commercial-utility reactors and, at one time, also included systems applicable for use in space (NERVA, et al). Recently, interest has been generated in development of a space power-reactor at the 100 kw level, the SP-100. (Also, concepts such as the rotating-fluidized-bed reactor have attracted attention.)

With the substantial technology base developed over the last four decades, many of the tools, techniques and data exist to develop high-power space-nuclear systems. The principal problem is operating lifetime. This problem is specific to nuclear systems, in terms of reaction-induced

damage and swelling, but common to all thermal power systems for space, in terms of creep, loss of fatique strength, integrity, etc. at the high temperatures required for rejection of waste heat. Those research tasks that are peculiar to nuclear power systems can be considered applied research and should be sponsored as part of programs to develop such systems. The more general problem area of material behavior at high temperatures, especially under conditions of mechanical stress and corrosion, is appropriate for basic research consideration. Similarly, problems associated with particular device concepts, (such as rotating-fluidized-bed reactors, selection of nuclear fuel packages, etc.), should be considered as applied to particular missions that demand these concepts. Analyses of nuclear safety issues and techniques also depend closely on the particulars of the mission and spacecraft, and apply only to space nuclear-power systems.

4. POWER CONVERSION

The research area in nuclear sources that is common to all systems based on thermal energy is the behavior of materials at elevated temperature. Such research would apply within a nuclear source, to thermoelectric and thermionic converters, to Brayton, Rankine, and other thermodynamic cycles, MHD generators, and finally to various stages of the heat rejection system. In the area of power conversion, in particular, there are two types of high temperature materials questions: 1) experimental data on solid and liquids above 2000°K and 2) physical understanding of phenomena at high temperature, including the means to specify and achieve desired behavior. The former question reflects the difficulties associated with performing experiments in the higher temperature regimes that may be suggested by system optimization studies (which in turn require performance data). The latter type of question

includes such concerns as the scaling of the figure of merit-temperature product in thermoelectrics, and approaches to preventing corrosion of high temperature, alkali-metal flow loops. A common research area is the interaction of high temperature materials at interfaces. The physical/chemical basis for preparation of materials, bonds, coatings, etc., can be examined in such research.

5. RADIANT SYSTEMS

Prime-power systems based on radiant energy exist in two different forms. Some systems utilize photons in proper energy ranges to convert radiant energy into electricity by direct interaction of photons with electrons, (photoelectric effect, microwave-,laser-receivers, etc.). Other systems absorb photons over a broad range of energies in a manner that converts radiant energy into heat, (scattering, reabsorbing, downshifting photon and particle energies in free and bound states). Heat is then converted into electricity by thermal methods, including thermoelectric, thermionic, and various dynamic cycles, (Brayton, Rankine, MHD, etc.) The two different forms of radiant energy system have quite distinct research problems.

For radiant-thermal systems, the concerns are essentially the same as for other thermal concepts. Basic research is needed on materials and material interfaces at high temperatures. (Such research has been mentioned in earlier sections). Direct radiant-electric systems involve research topics that range from design and fabrication of multi-layer (tandem) photocells that more efficiently utilize the solar spectrum, to understanding the interactions of electromagnetic radiation with plasmas(solid or gaseous) in the context of electrical power generation. The former topic will probably include fundamental research questions on the characterization and modification of matter and will be

closely related to other problem areas, such as thermoelectrics. Research on interactions with plasma might involve the utilization of transmitted laser radiation to excite plasmons, and could provide needed understanding of the coupling of randomly-phased radiation to plasma electrons.

An additional critical technology area for radiant systems based on solar power is the need for large structures to accumulate the required high levels of power. At 1 kw/m^2 incident power flux and 10% conversion efficiency, collection areas in excess of $10^4 m^2$ would be needed for megawatt electrical power levels. The interactions of space-plasma and fields with such structural areas provide additional research problems (that will occur also for large heat-rejection radiators, and possible Air Force payloads such as antenna arrays.)

6. MATERIALS AND CHEMICAL PHYSICS RESEARCH

The earlier sections have repeatedly noted the importance of obtaining data and understanding of materials at high temperatures, the behavior of interfaces between solids, liquids, gases, and plasmas, and the interactions of photons with matter. Facilities for obtaining data at elevated temperatures (2000°K), for controlling sample purity, especially at surfaces, and for evaluating longterm behavior of materials (e.g., creep, loss of fatigue stress) are far from trivial and are not generally available. An important area of concern is, therefore, the development of the means for conducting basic research, using either existing facilities, (created in response to particular device requirements), or new user-oriented facilities. (Related to the development of experimental tools is the sponsorship of educational programs that will provide researchers trained and interested in the area of high temperature material behavior). University-based programs, in close cooperation with government laboratories (e.g.,

AFWAL, NASA Lewis, LANL), can offer steady progress in the necessary long duration research tasks associated with the creation and evaluation of new materials.

Material modification techniques can be attempted, but considerable care must be taken to prepare and characterize samples. Progress has been made in such areas as ion bombardment to improve the film coefficient for heat transfer at surfaces, ion beam generation of diamond-like coatings, and deep impurity trapping to create new semiconductors. The number of possibilities and combinations is very great. Improved theoretical/ calculational tools will be necessary to evaluate data and to guide the selection of materials and techniques. Experimental techniques, with calculational support, will be needed that have considerable flexibility to characterize a variety of new materials and arrangements.

Ideally, it should be possible to design and fabricate special combinations of elements that will possess the energy levels, bandgaps, mobilities, etc. desired to achieve higher performance. In many instances, fundamental constraints will exist that prevent some combinations from occuring. Alternative combinations and techniques, however, may always be possible. With such an idealization in mind, it is useful for research in space prime-power to identify those characteristics that limit performance and those properties of materials at atomic and molecular levels that can provide significant improvements. Basic research can supply the experimental and theoretical techniques for performing such identifications.

7. THERMIONICS

Power generation using thermionics becomes attractive when high temperature sources are available to heat electrons directly out of a cathode. An anode at lower temperature can then be placed close enough to the cathode to collect significant electrical currents. Electron emission from metals is a strongly-increasing function of temperature so the anode can function even at a relatively high temperature ($\sim 1000^{\circ}$ K) which allows substantial reduction of the radiator area needed for heat rejection. Combined with high temperature sources (e.g., nuclear), thermionic conversion thus offers the potential for very compact prime-power systems.

Research problems in thermionics are in two main areas. High temperature operation requires understanding and control of materials at elevated temperatures, both within the converter itself and in the heat rejection system that can, in principle, operate with relatively high temperature waste-heat. The details of particle density and temperature distributions within the converter are a separate area of concern, since the efficiency of thermionic converter operation depends critically on the self-consistent potential distribution from cathode to anode. Improvements by altering electrode geometries, ionization/neutralization, etc. are predicted theoretically and can be examined. The particular details of thermionic converter design are subject to applications (e.g., in-pile operation is concerned with neutron effects). The ability to analyze, predict, and verify interactions of plasmas with electrodes and insulators, particle density and temperature distributions in alkali-metal discharges, etc. is a basic research goal appropriate to thermionic converters, MHD generators, and various electric propulsion schemes.

8. HEAT AND SYSTEMS

The final functional category in a space prime-power system is the rejection of waste heat. For intermittent use of short duration, waste heat can be stored in matter that is either ejected (e.g., open-cycle) or retained and cooled subsequently by other techniques at lower power. Steady-state operation in space requires heat rejection by radiation. For the temperature ranges of interest, and the materials available, such radiation follows a blackbody-like behavior and is thus a strong function of temperature ($\sim T^4$). Much of the effort in achieving high levels of heat rejection capability have been concerned with techniques for heat transport from converters to radiator panels.

A major component of such transport is generally the heat pipe, in which a self-pumping flow cycle is established by vapor-flow, condensation, and capillary return of liquid coolant. Although the operation of heat pipes has been demonstrated successfully, their use in complicated geometries (e.g., sharp turns) and improvement in specific power flux, reliability, etc. require greater understanding in areas such as surface wetting, capillary flow, two-phase flow stability, condensation, etc. The effects of surface preparation, coatings, geometries, material compatibility at high temperature, etc. need to be evaluated. Basic research is needed on two-component flows and interactions of liquids and condensing vapors with surfaces. Such research could be applicable to two-phase flows in heat transfer systems, in thermodynamic cycles (dynamic conversion systems), liquid-metal MHD generators and liquid-radiator schemes.

The use of liquid-films or -droplets to create a large, low mass surface for heat radiation has been proposed for high-power space systems. The particular schemes have problem areas that would need to be addressed in exploratory development. More general topics, however, for basic research interest include the interactions of liquids with space-plasmas (individually and in clouds or streams) and heat transfer, wetting, stability, etc. of liquid streams and droplets interacting with surfaces.

The interactions of large structures (solid or liquid) with space-plasmas, fields, and radiation should be examined on a general basis to provide guidance for design and evaluation of particular systems, (e.g., radiators, solar collectors, antennas, shields, mirrors, etc.). Such interactions include both shortterm events (surge currents, voltages in storms) and longterm degradation (e.g., electro-corrosion, drag, etc.). Basic material data are also needed for the design of large space structures (thermal, electrical, mechanical characterization of construction materials and predictions for new materials).

V. SUMMARY OF BASIC RESEARCH AREAS FOR SPACE PRIME-POWER

The preceding section provides a rapid survey of space prime-power technology and the research problems associated with particular functional or technical categories. Although there are many particular research topics that require attention, three areas of basic research are indicated that would support future development of prime-power for high energy space systems:

1. Characterization and Design of Materials
2. Fluid Interactions
3. Plasma Interactions

Within these three areas are distinct, but related topics. The last two areas will couple to the first area for those interactions that depend upon material properties at surfaces. Delineation of the three areas above can be associated with the technical specialties that may be required for successful research in these areas: solid-state physics, fluid mechanics, and plasma physics, respectively.

1. CHARACTERIZATION AND DESIGN OF MATERIALS

There are two extremes of approach and need in this research area. The basic physical chemical laws governing the structure of matter can be examined, extended, and utilized to devise new materials and combinations of materials that have desired properties to advance space prime-power. Material modification techniques (e.g., ion bombardment, impurity trapping) can be developed, guided by theoretical and experimental tools. Eventual applications will be to improved solar cells (e.g., tandem), lower corrosion, new catalysts, etc.

A more mundane avenue of endeavor is the characterization of material properties, especially at high temperatures (> 2000° K). Experimental facilities and techniques are required for life-testing structural materials, measuring creep stress characteristics, loss of fatigue strength, etc. Characterization of structural properties is also needed for new materials at lower temperatures (for large space-structures, high pressure fuel-cells, etc.)

2. FLUID INTERACTIONS

Flow of liquids and gases through various structures and under various conditions of temperature and pressure is found in many space prime-power concepts. Very often the flow interacts with boundaries resulting in corrosion or wear. Boundaries guide and support desirable flow behavior as well (e.g., capillary flow in heat pipes). Factors affecting the interactions of liquids and solids need to be examined. For example, the influence of surface preparation on wetting and heat transfer. Interaction of flows with suspended liquid or solid droplets is a concern in several heat transfer schemes. Characterization of fluid material properties at high temperature is also necessary (e.g., potassium, tin) in order to predict behavior for dynamic conversion, heat transport, heat rejection, etc. Chemical effects on boundaries (corrosion, fuel-cell operation, etc.) can be examined in conjunction with surface modification techniques.

3. PLASMA INTERACTIONS

Plasmas occur in space prime-power systems both internally (thermionic diodes, MHD generators) and externally (space-plasma surrounding radiators or collectors). The distributions of particle density and temperature within

power converters are critical to performance. Such converters include not only the standard thermionic and MHD techniques but also new concepts (e.g., photon conversion to electricity in solid or gaseous plasmas). The interactions of plasmas with electrodes and insulators (particle bombardment chemical reaction, erosion) are important to system lifetime. High energy plasma particle bambardment of insulators, liquid-films, droplets, etc. can cause longterm degradation of power systems. Short term electrical surges supported by space-plasmas can damage large structures associated with high power space systems. Theoretical and experimental examination of plasma interactions in the context of space prime-power systems can guide the development of improved converters, and also avoid otherwise unforeseen difficulties with large space-system operation.

VI. CONCLUDING REMARKS

The descriptions of basic research areas in Sections IV and V are provided as general guidance to prospective researchers interested in contributing toward future high-power space systems. Specification of particular research tasks has been consciously avoided in order to emphasize the breadth of potential research and to prevent concentration on nearterm developmental concerns. A substantial amount of excellent applied research has been done (and continues), as evidenced by the Bibliography. For the limited resources that can be provided to basic research to have significance, efforts must delve deeply to apply broadly.

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